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Hyper-X Stage Separation—Simulation Development and Results

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Abstract

This paper provides an overview of stage separation simulation development and results for NASA's Hyper-X program; a focused hypersonic technology effort designed to move hypersonic, airbreathing vehicle technology from the laboratory environment to the flight environment. This paper presents an account of the development of the current 14 degree of freedom stage separation simulation tool (SepSim) and results from use of the tool in a Monte Carlo analysis to evaluate the risk of failure for the separation event. Results from use of the tool show that there is only a very small risk of failure in the separation event.

Introduction

The development of reusable launch vehicles holds great promise as the key to unlocking the vast potential of space for business exploitation. Only when access to space is assured with a system which provides routine access with affordable cost will businesses be willing to take the risks and make the investments necessary to realize this great potential. The current NASA second generation access to space programs (X-33 and X-34) are steps on the way to enabling the routine, scheduled access to space. Unfortunately, while a great improvement over current systems, the cost per pound delivered to orbit for currently proposed systems will still be greater than that required to exploit space for many business uses. One of the limiting factors in potential cost reductions for chemical rockets is the Isp limit.

The use of airbreathing engines holds potential for very significant increases in Isp which could result in a significantly lower cost per pound to orbit. The National Aero-Space Plane program (NASP), which was canceled in 1995 as unaffordable at that time, was a joint NASA/U.S. Air Force effort to develop a single-stage-to-orbit, airbreathing vehicle. However, while the NASP was never completed, the NASP program developed a significant number of technologies which only await demonstration before they will begin to be accepted for use in future aerospace vehicles. Key among these technologies is airbreathing engines for hypersonic flight. NASP brought the materials and design methods for scramjet (supersonic combustion ramjet) engines to the point that efficient engines and practical vehicles which use them can be developed. One of the major requirements to have these technologies accepted is a flight demonstration. In the spirit of "Faster, Better, Cheaper," NASA has initiated the Hyper-X program to demonstrate that scramjet engines can be designed, constructed, and will operate at the high Isp levels necessary for use in access to space vehicles as an initial step to this end.

The NASA Hyper-X program employs a low cost approach to design, build, and flight test three small, airframe-integrated scramjet powered research vehicles (X-43) at Mach numbers of 7 and 10. The research vehicles will be dropped from the NASA Dryden B-52, rocket boosted to test point by a Pegasus first stage motor, separated from the booster, and then the scramjet powered vehicle operated in autonomous flight. Tests will be conducted at approximately 100,000 ft. (depends on Mach number) at a dynamic pressure of about 1000 psf. To the program's knowledge there has never been a successful separation of two vehicles (let alone a separation of two non-axisymmetric vehicles) at these conditions. Therefore, it soon became obvious that the greatest challenge for the Hyper-X program was, not the design of an efficient scramjet engine, but the development of a separation scenario and the mechanisms to achieve it. After the stage separation scenario and mechanisms were developed and numerous wind tunnel and ground tests were conducted a means to evaluate the risk associated with the separation event was desired. This paper will describe the development of the 14 degree of freedom simulation tool (SepSim) used in the risk assessment and present some of the results from a Monte Carlo analysis utilizing the tool.

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Symbols and Abbreviations

AEDC	U.S. Air Force Arnold Engineering & Development Center
Alpha	Angle Of Attack
ß	Angle of Side Slip
DFRC	Dryden Flight Research Center
FCGNU	Flight Control, Guidance, and Navigation Unit
fps	feet per second
HXLV	Hyper-X Launch Vehicle
HXRV	Hyper-X Research Vehicle
INS	Inertial Navigation System
Isp	Specific Impulse
LaRC	Langley Research Center
M	Mach number
NASP	National AeroSpace Plane
psf	pounds per square foot
q	dynamic pressure

Background

The method and evolution of the Hyper-X stage separation scenario has been discussed in reference 1. In short, the Hyper-X research vehicle is attached to the booster adapter by 4 explosive bolts which fire at the initiation of the separation event. Firing of the explosive bolts is followed by the research vehicle being pushed forward by 2 pyrotechnically actuated pistons which push through the research vehicle's cg. The pistons push for a distance of 9 inches in about 0.100 second with a force of approximately 22,000 lbs. This push yields a relative velocity between the two vehicles of greater than 13 ft./sec. The goal of the separation event is to separate the two vehicles cleanly, with no re-contact and with the research vehicle able to achieve the target 0 degrees side slip, 2 degrees angle of attack attitude (within +/- 0.5 deg.) for the start of the engine test sequence 2.5 seconds after separation (Figure 1).

Scope

In order to assess the viability of the separation event a 6 (research vehicle) + 6 (booster) + 2 (pistons) degree of freedom simulation tool (SepSim) was developed under contract to LaRC by Analytical Mechanics Associates. SepSim models the highly nonlinear and dynamic event of the HXRV separation from the HXLV. This tool models all of the vehicle dynamics, separation mechanics, and aerodynamics for both vehicles utilizing an ADAMS solver (ref. 2). The ADAMS tool is an industry standard simulation code. ADAMS supplies general multi-body 6 degree of freedom equations of motion, simulation integration, and input/output capabilities. The SepSim team supplied user subroutines for aerodynamic forces and moments, control system characteristics, atmosphere modeling, bolt and piston characteristics, HXLV and HXRV actuator characteristics etc. SepSim begins when the command is given to blow the explosive bolts attaching the two vehicles and ends 2.5 seconds later when the HXRV has cleared any influence of the HXLV and has recovered to the desired state to begin the cowl open portion of the flight test. The separation event will be deemed to have been successful if the HXRV reaches that point.

Models

SepSim models the aerodynamics of both HXRV and HXLV utilizing an extensive database obtained from comprehensive wind tunnel tests at both Langley and AEDC (ref. 3). The database contains vehicle alone characteristics as well as interference aerodynamics for various relative positions of the two vehicles (ref. 4). State of the art CFD tools were used to quantify ground to flight scaling and unsteady flow phenomena during the dynamic separation event (ref. 5) as well as extending the wind tunnel database to relative vehicle orientations not achievable in the wind tunnel. Uncertainties in the aerodynamics were developed by Dr. Rodney Bowersox of the University of Alabama (ref. 6) under contract. The twelve aerodynamic coefficients for any given relative orientation are extracted from the database as a function of the angle of attack and side slip of the HXRV as well as the Euler distances and angles between the center of masses of the HXRV and HXLV (Figure 2).

The mass properties used in SepSim were obtained from a number of sources. The HXLV mass properties were received from Orbital Sciences Corporation and were derived from their extensive Pegasus database with appropriate modifications for the HXLV application. The booster adapter (including internal systems) mass properties were obtained from Micro Craft, the constructor. The HXRV mass properties were derived from weight and inertia tests conducted by NASA DFRC (Figure 3). All of the mass properties used in SepSim were checked by comparing them with properties predicted by structural analysis codes.

The timing of the explosive bolts was modeled on the results from a number of tests conducted at Orbital Sciences. These tests included a number of single bolt firings in joints duplicating those used in the vehicle up through a full scale separation test (Figure 4) which included the whole ordnance train from the Orbital Ordnance Driver Modules (ODM's) in the HXLV which initiate the pyrotechnics to the explosive bolts and pistons.

The ejector pistons were modeled based on a number of piston tests conducted at Orbital Sciences to measure/verify their timing and force profiles (Figure 5). In addition, piston side load tests were conducted at DFRC (Figure 6) to measure friction and deflection characteristics in the event that the normal or side loads on the HXRV are non-zero during the separation event. The resulting model was compared with data obtained during the testing conducted during the qualification of the pistons for use in their original application in B-1 bomb ejector racks.

The initial HXLV/HXRV stack state(s) at the time of separation were obtained from a Monte Carlo analysis of the launch run by Orbital Sciences. The set of results from the Orbital simulations was fed into SepSim as a varying set of initial conditions.

The reference atmosphere used in SepSim is the Dryden Range Reference Atmosphere (for the month of flight) with Vandenberg wind profiles added. This is the same atmosphere model used by the HXRV guidance and control software. GRAM95 (ref. 7) atmospheres for all 12 months with Vandenberg winds are available separately to SepSim to be selected from randomly as inputs in the Monte Carlo analysis.

The flight controls are modeled based on descriptions provided by Boeing which developed the flight control laws. The guidance system model is based on one supplied by Honeywell, the manufacturer of the FCGNU. Errors in the output of the FCGNU are modeled linearly and based on equations adapted from reference 8. The error models were validated by comparing predicted errors with those from a variance analysis provided by Honeywell. The FCGNU error states are modeled as constants over the 2.5 seconds of the simulation. The states include position error, NED velocity error, tilt and azimuth error. Possible FCGNU misalignment is also modeled. The error states and misalignment result in variable feedback errors in angle of attack, Mach number, dynamic pressure, velocity, bank angle, pitch angle, and body rates. The error states are initialized in two ways: with closed form equations derived from the nominal boost trajectory and with pre-calculated errors (error equations integrated for specific boost trajectories).

The HXRV control surface dynamics are modeled as the combination of two subsystems; actuator and freeplay. A second order model was initially based on the Boeing requirements specification. The model was subsequently revised based on the Moog (actuator manufacturer) high fidelity math model. This math model has been further refined based on acceptance tests, actuation tests and hysteresis testing at DFRC. Final refinement was based on aircraft-in-the-loop testing at DFRC. The HXLV actuator model was provided by Orbital Sciences.

Model and Simulation Validation

Validation of SepSim was performed at three levels. The input variables, implementation, and results from the simulations were all reviewed by those that contributed the respective models. Modular level checks were performed by comparing results with those from independently constructed check models. Integrated level checks were performed by comparing SepSim results with the results from a totally independent six-degree-of-freedom simulation developed by DFRC.

Figure 7 shows the procedure for the modular level validations performed on the models for actuators, aerodynamics, atmosphere, controls, INS error, pistons, and separation deltas. A typical comparison between the SepSim model and that from the independent Simulink® model. Here the SepSim and Simulink® results match exactly. Figure 8 shows how the wing actuator model was compared against test results. Again, the comparisons are quite good.

An integrated level check of the simulation implementation is shown in figure 9. Here 5 examples of simulation results from SepSim and the DFRC simulation (RVSim) are compared. For the 2.5 seconds of interest for the separation event there is almost perfect overlay of the two separation simulations.

Re-contact Analysis

The re-contact analysis utilizes DIVISION™ Mockup software by Parametric Technology Corporation (PTC). The software utilizes three dimensional models of the HXLV, HXRV, and adapter done in Pro-E software and the positions and orientations of the vehicles provided by SepSim and determines whether the bodies interfere. For cases where the bodies did not interfere (all) one and two inch “shells” were built in the Pro-E models around the various bodies and the DIVISION™ Mockup software run again to determine if there were any cases where the vehicles were within those bounds.

Results

A Monte Carlo analysis of the separation event was conducted using SepSim with the previously discussed models and uncertainties. Two thousand cases were examined. Of the 2000 cases 7 did not complete to 2.5 seconds. There were 11 cases that exceeded +/- 10 degrees of alpha or beta during the 2.5 seconds of separation. Eight cases did not satisfy the alpha and/or beta requirements at 2.5 seconds. These 26 cases are being classified as failures. This amounts to only 1.3% and yields high confidence that the separation event will be successful.

There were no cases of re-contact between the HXRV and the adapter. There was one case within 1 inch proximity and 54 cases within two inches of the adapter.

Figures 10 to 12 show angle of attack, angle of sideslip, and roll angle time histories for the 1993 cases which ran to completion. These plots illustrate the vast number of successful separations predicted by SepSim.

Figure 13 illustrates the alpha and beta target for successful engine operation (small box centered around 0 degrees beta and 2 degrees alpha) and the number of cases which fall within. Most cases fall within the box (88.2% for alpha target and 100% for beta target). Also indicated on the plot is the allowable target determined from tests of a spare flight engine at flight conditions in the Langley 8-ft. High Temperature Tunnel (ref. 9). All of the cases fall within this larger box which has been shown to result in successful engine operation. It must be also noted that the majority of the variation in the alpha and beta at 2.5 seconds is due to an assumed 0.75 degree uncertainty in the INS position in the HXRV. When this uncertainty is removed the results fall within the target box. The project is taking great pains to ensure that the position of the INS is accurately known so that confidence is high that the HXRV will end up within the target box during the actual flight.

Concluding Remarks

This paper discussed highlights of the stage separation simulation tool developed to model the separation of the Hyper-X research vehicle from its launch vehicle. A Monte Carlo analysis of 2000 cases utilizing the tool shows that less than 1.5% of the cases fail through either numerical instability or loss of control. Of the successful cases 88.2% met the alpha and 100% met the beta targets at 2.5 seconds. (The program is actively working to eliminate the major cause of not meeting the alpha target and believes that the actual flight will meet the targets.) Of the successful cases, there were no direct re-contacts, 1 case came within 1 inch, and 97.3% had at least 2 inches of clearance. Histories of variable’s means and standard deviations indicate that 2000 cases are statistically significant and there is high confidence in being able to achieve a successful engine test beginning at 2.5 seconds after separation.

Acknowledgments:

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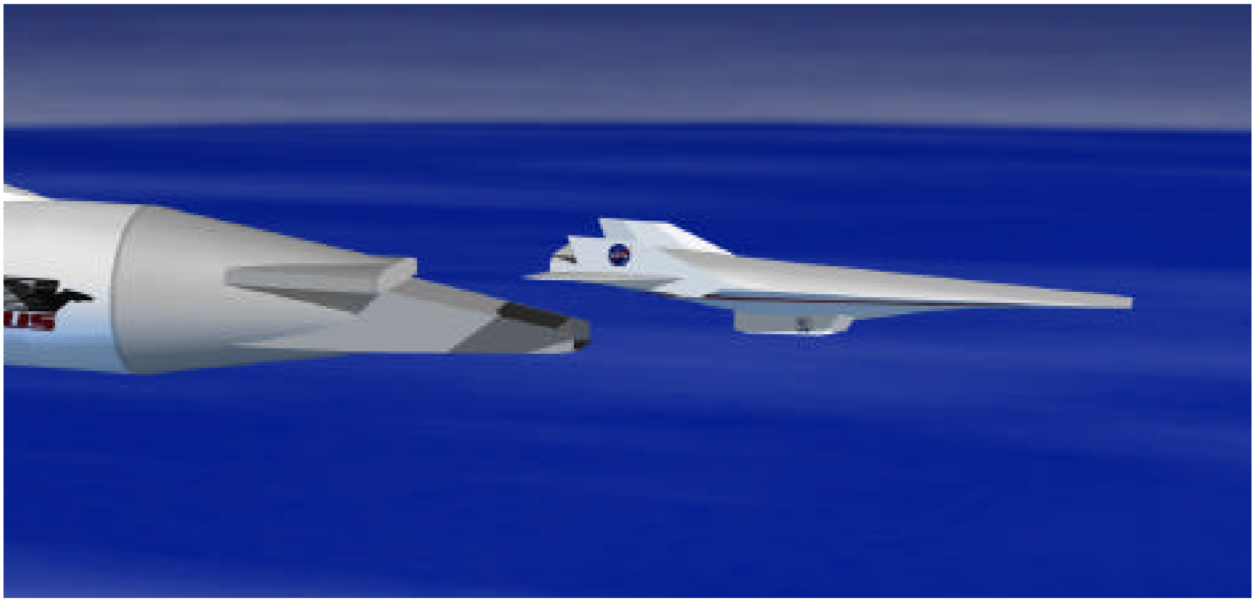

Figure 1. Artist's Concept of Successful Separation.

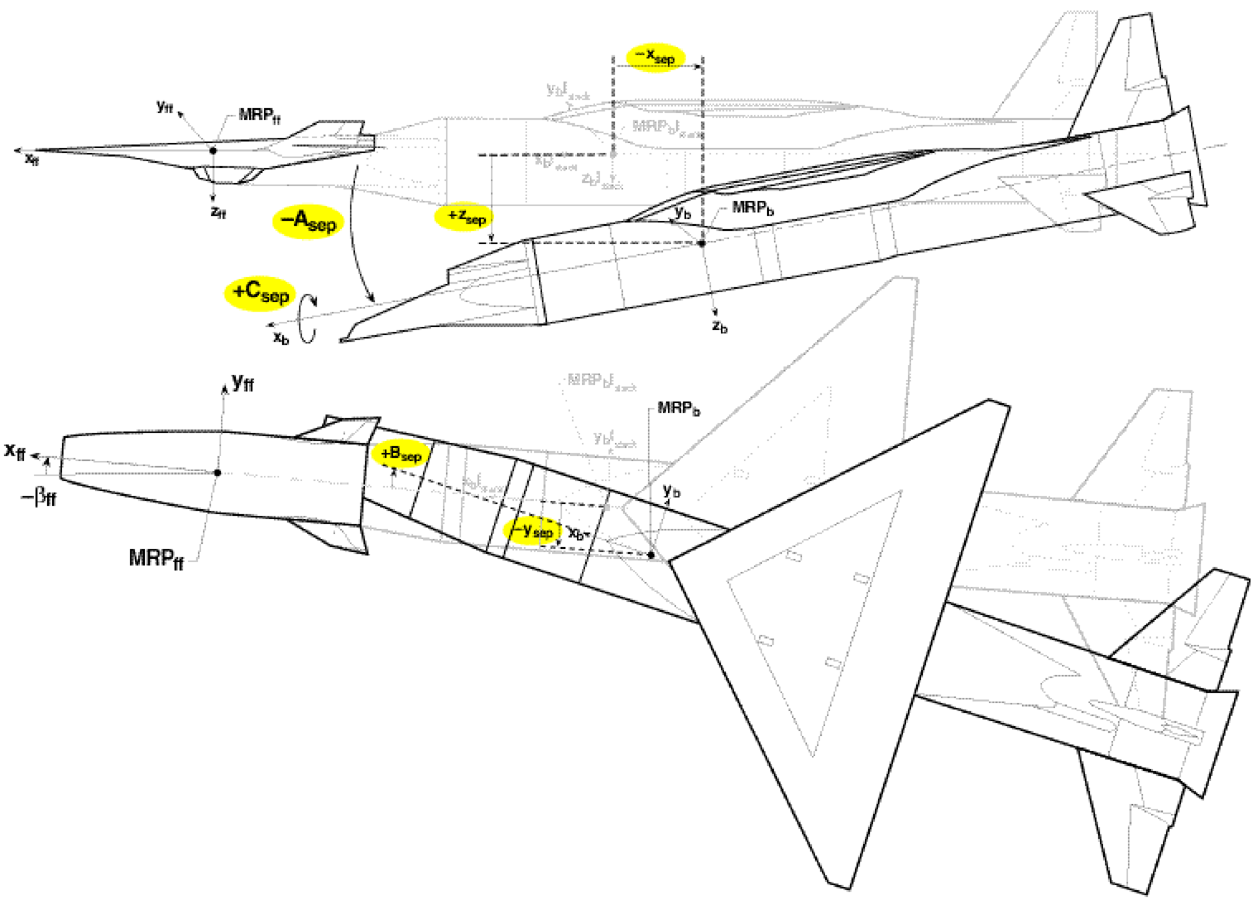

Figure 2. Euler HXLV/HXRV Distances and Angles.

Figure 3. HXRV Undergoing Mass Properties Testing at DFRC.

Figure 4. Full Scale Separation Test.

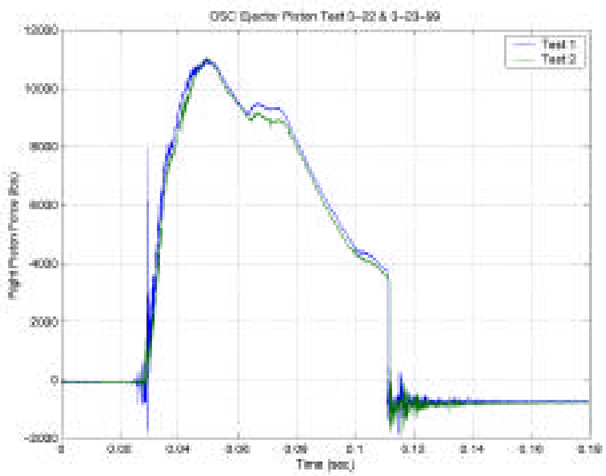

Figure 5. Typical Ejector Piston Test Results (Force).

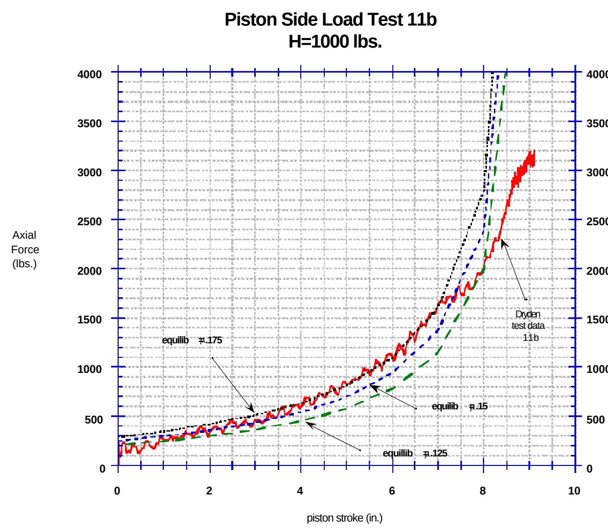

Figure 6. Piston Side Load Test Results.

Procedure:

- **Execute SepSim**
- **Capture model i/o and Monte Carlo variables**
- **Pipe input through check model**
- **Compare outputs**

Covered Models

- **Actuators**
- **Aerodynamics**
- **Atmosphere**
- **Controls**
- **INS Error**
- **Pistons**
- **Sep. Deltas**

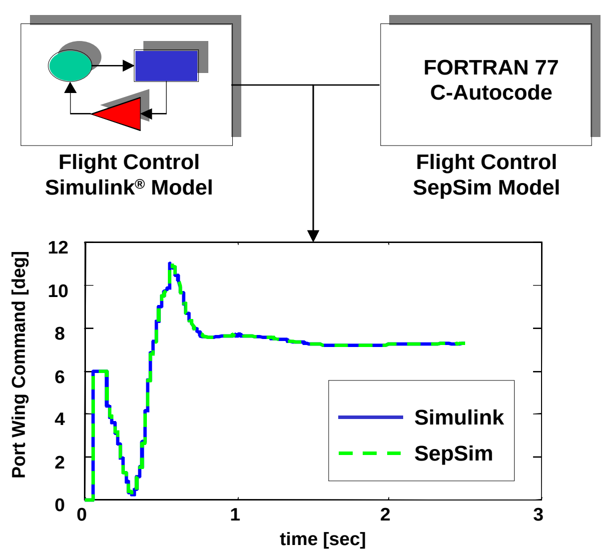

Figure 7. Modular Level Validation of Flight Control Model By Comparison With Independent Model.

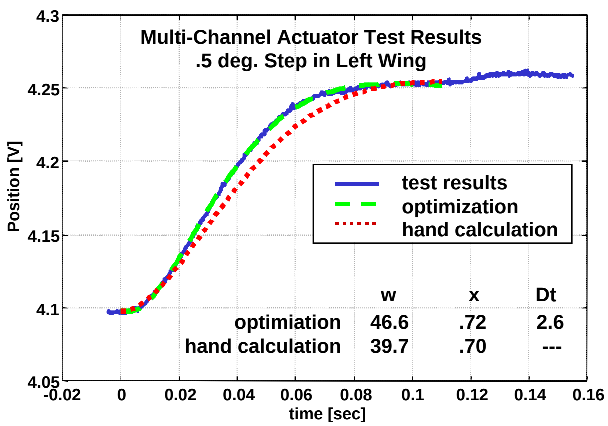

Figure 8. Modular Level Validation of Actuator Model By Comparison With Test Results.

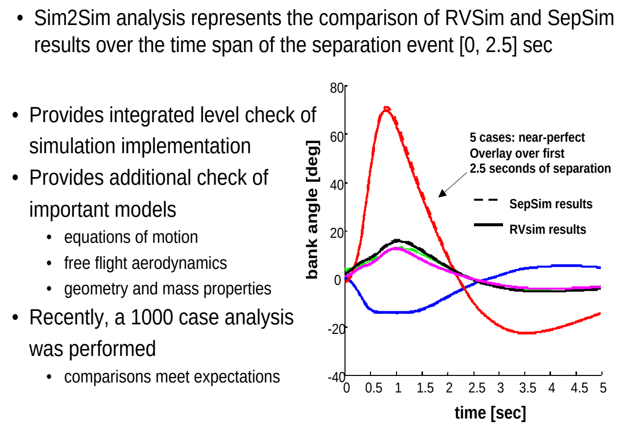

Figure 9. Typical Integrated Level Validations Comparing Results of 5 Cases From SepSim and DFRC Simulation.

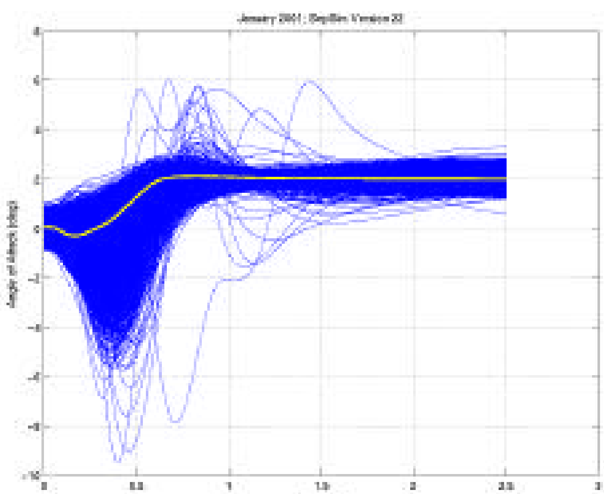

Figure 10. Angle of Attack Time Histories for 1993 Cases Which Ran to Completion.

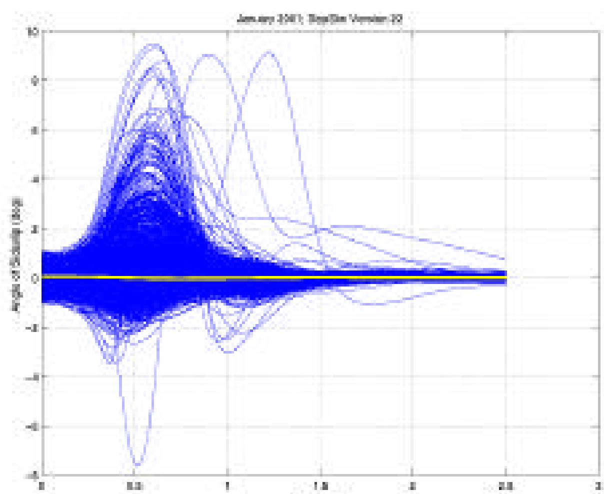

Figure 11. Angle of Side Slip Time Histories for 1993 Cases Which Ran to Completion.

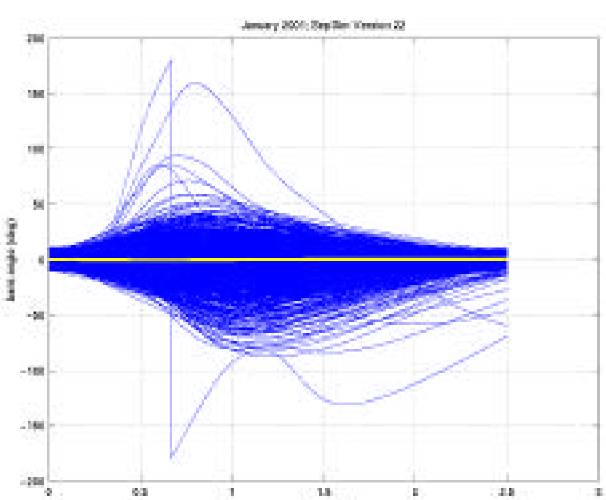

Figure 12. Roll Angle Time Histories for 1993 Cases Which Ran to Completion.

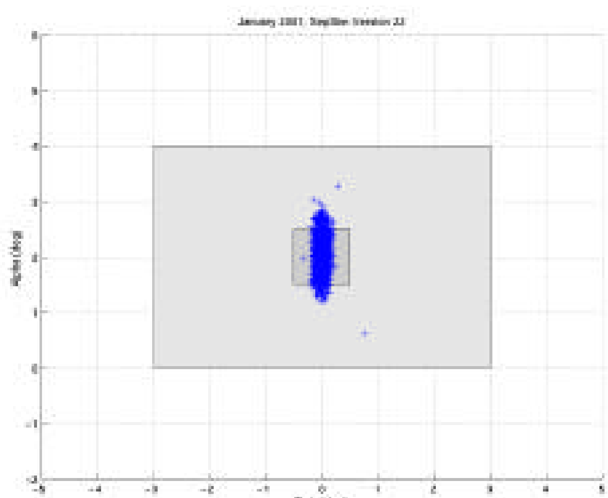

Figure 13. Angle of Attack and Side Slip Targets and Acceptable Ranges at 2.5 Seconds Compared with Results From 1993 Cases.